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ORIGINAL PAPER

Predisposing and triggering factors of large-scale landslides in Debre Sina area, central Ethiopian highlands

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Abstract

A large number of landslide events have repeatedly struck the border zone of the northwestern plateaus of Ethiopia. Debre Sina area is one of the most tectonically active areas located along the western margin of the Afar depression, which is frequently affected by landslides. Despite that, urban and rural development is currently active in almost the entire area. It is crucial, therefore, to understand the main causes and failure mechanisms of landslides in the Debre Sina area and its surroundings. The present study investigated landslides using field mapping of geological and geomorphological features, remote sensing, geomorphometric analysis, structural analysis, rainfall data, landslide inventory, and earthquake data. The results of the study indicate that large-scale and deep-seated landslide problems appear to be caused by complex geological settings and rugged topography. In particular, the location and morphology of the Yizaba Wein and Shotel Amba landslides are strongly controlled by geological structures. Their flanks are bounded by high angle faults, and their main basal failure surfaces have developed within a W–E striking eastward-dipping normal fault zone. The complex litho-structural and morphologic settings play a vital role in controlling the geometry of the slip surfaces and the stability of the landslides.

Keywords Failure mechanisms · Landslides · Natural hazards · Rift escarpment · Ethiopia

Introduction

Landslides and related ground movements are among the common geo-environmental hazards in many hilly and mountainous terrains of the world. There have been several landslide events in Ethiopia that have resulted in considerable socio-economic impact. The highlands of Ethiopia are highly susceptible to slope instability due to heavy rainfall and land-use change, including the effects of road construction (Woldearegay 2013). Urban and rural development is currently taking place in almost all areas. Landslides represent one of the main constraints for the development of road infrastructures in many parts of Ethiopia. As Woldearegay (2013) mentioned, several authors indicated that modification of slope geometry through natural or man-made processes could influence the stability of slopes (Varnes 1978; Greenway 1987; Bell 1999). Nowadays, there is a significant increase in landslides in Ethiopia as the road network has continued to expand over recent decades. This problem is also significant in the Debre Sina area and its surroundings. Active extensional tectonics, high heat-flow, and intense volcanism associated with the East African Rift System are the main factors for frequent hazardous geological phenomena in Ethiopia (e.g., Chorowitz 2005; Abebe et al. 2007; Agostini et al. 2011; Kycl et al. 2017). According to Ayalew (1999), major faults that run parallel to the Main East African Rift (MER) have formed release surfaces for structurally controlled deep-seated landslides.

Most of the large-scale landslides in Ethiopia have occurred along the MER scarps and also developed in plateau regions (e.g., Abramson et al. 1996; Ayalew 1999; Temesgen et al. 2001; Ayalew and Yamagishi 2004; Ayenew and Barbieri 2005; Nyssen et al. 2006; Fubelli et al. 2008, 2013; Moeyersons et al. 2008; Coltorti et al. 2009; Van Den Eeckhaut et al. 2009; Abebe et al. 2010; Zvelebil et al. 2010; Vařilová et al. 2015). The margins of the western Afar

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depression are currently under threat with the problem of landslides in many places. Particularly, the Debre Sina area is known for its several landslides that have occurred in the past (EIGS 1979; Schneider et al. 2008; Woldearegay 2008; Abay and Barbieri 2012; Alemayehu et al. 2012; Kropáček et al. 2015; Meten et al. 2015). There is also evidence of active landslides in the area. As stated by different researchers (Schneider et al. 2008; Abebe et al. 2010), the landslides in the rift margins of Ethiopian highlands are associated with deep-seated and structurally controlled deformations which require a detailed understanding of the geological and structural settings in order to clearly define the failure mechanisms. Despite that, less work has been conducted on landslides in the study area and its surroundings as the area is hardly accessible.

A large-scale landslide incident occurred in the study area at Yizaba Wein and Shotel Amba localities on September 13, 2005, and the slope instability problem still remains very active. Adequate characterization of landslides requires a deep understanding of the causes and failure mechanisms. This, in turn, requires a detailed study of the geology, topography, and physical properties of rocks and soils that occur in the areas forming unstable slope profiles. This study focuses on the 2005 large-scale landslide and recently reactivated landslides, which were induced by a combination of specific local conditions and external factors. This work aims at understanding the processes leading to the propagation of slope failure, the influencing factors, and the failure mechanisms based on data from field observations focusing on the geological and topographical conditions of the area, morphometric analysis, tectonic activity, hydrometeorology, and detailed evaluation of representative landslides with identical features and frequent reactivation that are imposing potential risks on the local residents and nationally important infrastructures passing through the area.

The study area

Debre Sina is situated in the border zone of the central-western highlands of Ethiopia about 190 km north of Addis Ababa, where the MER widens into the Afar depression (Fig. 1). The study area is bounded to the north and south by the UTM 1077165 m N and 1,108,635 m N; and to the west and east by the UTM 571065 m E and 601,125 m E. It covers an area of 946 km^2, with an elevation ranging from 1154 to 3691 m above sea level (a.s.l). The area comprises an extremely steep escarpment and a narrow strip of the plateau (Fig. 1). The escarpment comprises steep mountain chains and rugged valleys which drain into the central-eastern and western lowlands of Ethiopia. The study area is flanked by the lower and upper normal faults and the Tarmaber–Mezezo mountain chain. The climate of the area is sub-humid to humid with an average annual precipitation of about 1812 mm distributed with strong seasonality, having maxima in summer and spring. Debre Sina is one of the wettest parts of the country with a bimodal rainfall, with peaks in the months of June to August. The average maximum temperature is 25 °C and, the average minimum is 10 °C.

The western margin of the study area was produced during the Tertiary-Quaternary extensional phase, which was accompanied by down-warping of the Afar Depression and rift-ward tilting of faulted blocks (Zanettin and Justine-Visentin 1974; Almond 1986; Mohr 1986). The outcropping bedrock consists of a sequence of Tertiary Trap Volcanic Series: Ashangi basalt formation and Tarmaber basalt formation (Mohr 1971; Kazmin 1973; Zanettin et al. 1974; Kazmin 1979). The possible seismic source zones are very near to the study area (Ayele 2009).

Materials and methods

This study was started by compiling and reviewing pertinent secondary data. Topographic maps, regional geological maps, and satellite images were collected from Ethiopian Mapping Agency, Geological Survey of Ethiopia, and US Geological Survey, respectively. Detailed fieldwork investigations were carried out from April to June 2016, October to November 2017, and June 2018. The fieldwork was accomplished along selected traverse lines to cover the study area, focusing on the topographical and geological settings. Following the traverse lines, many observation points were selected in addition to the delineation and mapping of the past landslides by Google Earth imagery. The landslide inventory was obtained based on a 1:50,000 scale using aerial photographic interpretations for delineation and identification of past landslides and geological and geomorphological field mapping in the Debre Sina area and its surroundings. The distribution of landslides was examined in the context of geology (lithology and structure), topographic slopes, rainfall-landslides relationships, and earthquakes. There were new landslide occurrences during the fieldwork. A number of surface discontinuity measurements were conducted, and their kinematic relations with respect to the general slope trend were determined using SSWIN 2.2 stereographic projection facilities in a lower hemisphere equal area net. These have allowed visualization of the main structural trends and interpretation of their effects on the general conditions of stability of the lithological units.

Geological structures of the area were extracted from Landsat images (Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) and fieldwork to visualize their relationships with large-scale and deep-seated landslides. The images have been interpreted using Erdas Imagine 2014 by applying different enhancing and band composition techniques and digitized using ArcGIS 10.5. Structural

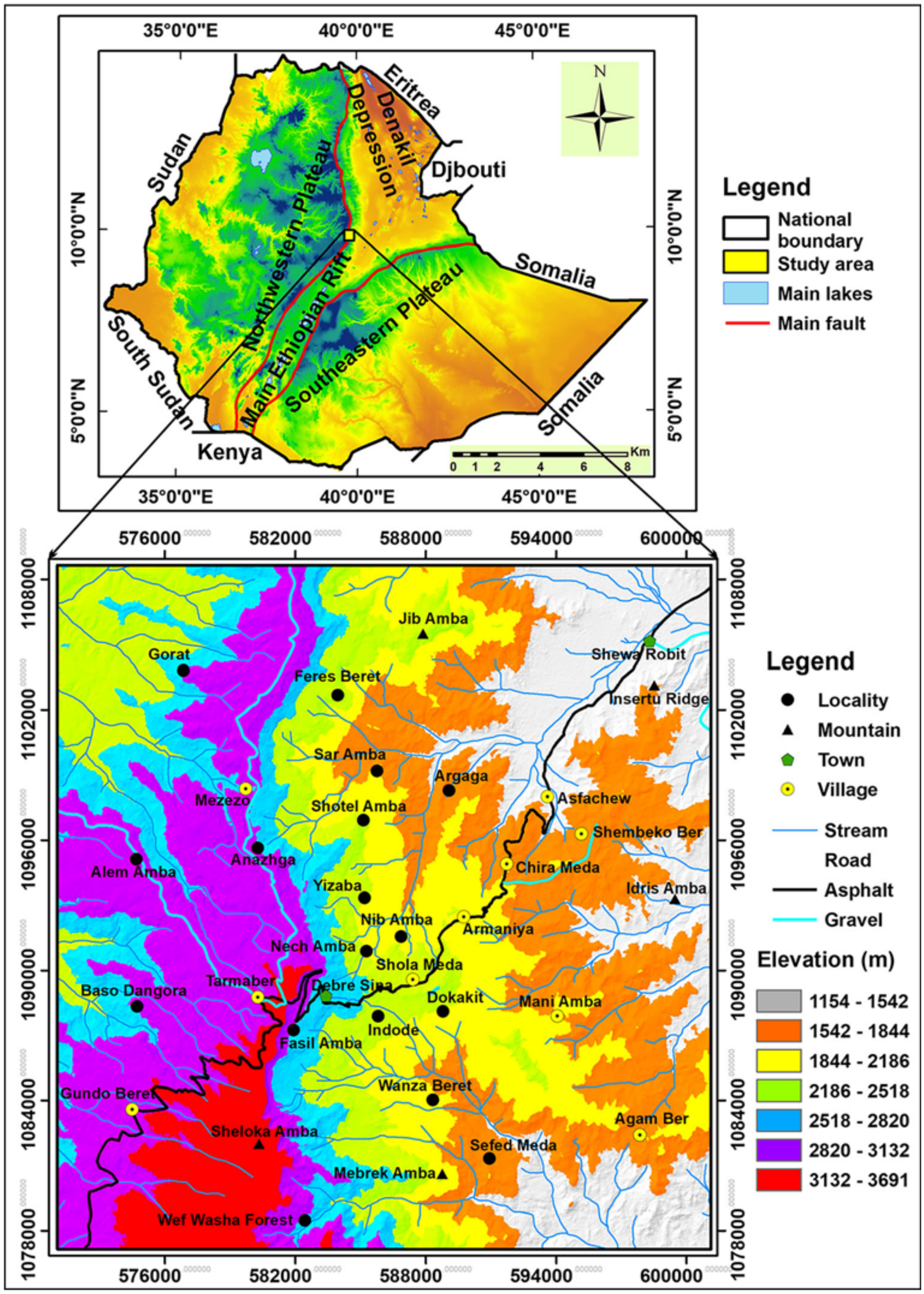

Fig. 1 Location map of the study area

measurements of faults, fractures/joints, and lineaments were conducted to reveal the structural predisposition of a slope to sliding. The strike and dip of the fault planes and fractures/joints detected in each structural station are reported in stereographic diagrams. Moreover, the geomorphic property of the area was generated from DEM data using GIS utilities to outline the different geomorphic characteristics and landforms in the area. Accordingly, the GIS and remote sensing (RS) analysis were used to produce new geologic, structural, and geomorphologic maps of the area. Processing of the DEM was carried out using a high-resolution satellite image in a Geographic Information System (using ArcView 3.3/ArcGIS utilities 10.5 and ILWIS 3.3) to extract elevation, slope gradient, and slope aspect, which are key to identify significant features of landslide events. These parameters are useful for the assessment of the geomorphology of the area. Besides this, Erdas Imagine 2014, Global Mapper 18, and CorelDRAW X7 were used for database creation, image processing and interpretation, spatial data analysis, and high-quality output maps and illustrations.

More than 40 years (1974–2016) of rainfall records from the Debre Sina station were collected from the National Meteorological Agency of Ethiopia (NMA). These data were analyzed to assess the distribution of precipitation variations and the long-term development of rainfall in the study area. Furthermore, daily data from the last 43 years were used to calculate the total annual precipitation in the years and subsequently compared with the landslide occurrences/reactivations.

Results

Geology and geomorphology of the study area

The outcropping lithology in the study area is represented by five Tertiary volcanic units associated with volcanic ash and two Quaternary superficial deposits (colluvial and alluvial deposits) (Fig. 2). Aphanitic basalt-porphyritic-agglomerate units crop out in the gully areas and series of cliffs and benches in deeply dissected valleys (Fig. 2). The basalt is grayish-black to black or reddish-brown colored and fine to medium-grained. It has a vitreous appearance, vesicular to amygdaloidal with clearly developed columnar joints and intense fracturing, and exhibits spheroidal weathering. The porphyritic variety is black to grayish-black, medium to coarse-grained, massive, with plagioclase and olivine phenocrysts. The agglomerate contains angular to sub-rounded glassy basaltic rock fragments as groundmass ranging from few millimeters to few centimeters. There is a paleosoil ranging in thickness from 10 to 20 cm between the porphyritic basalt and aphanitic vesicular basalt. Springs and seepage emerge at the contact between the basalt and the overlying colluvial sediments.

The ignimbrite-tuff-volcanic ash unit is widespread in the lower parts of the escarpment. The association mainly consists of pumiceous lapilli tuff and volcanic ash with subordinate ignimbrite, trachyte, and rhyolite. The ignimbrite beds form gentle to steep slopes, elongated ridges, and isolated valleys (Fig. 2). The ignimbrite is fine to medium-grained, highly consolidated, laminated, and moderately to highly fractured and weathered. The tuff is medium-grained, massive, weakly to moderately welded, often weathered, and friable, and exhibits horizontal layering. The volcanic ash is fine-grained, locally exhibiting sub-horizontal stratifications. The ignimbrite-tuff-volcanic ash beds form small cliffs, are highly altered and intensely weathered, and are vertically jointed and highly shattered by faulting. There are also dikes about 60 cm to 1.50 m thick which are fine-grained and glassy in texture with N35°E, N60°E, and N20°W strike directions.

The porphyritic basalt-scoriaceous agglomerate unit consists of dominantly porphyritic basalt and scoriaceous agglomerate with subordinate aphanitic basalt and vesicular basalt. The rock exhibits notable textural and compositional variations vertically: aphanitic basalt, porphyritic basalt, agglomeratic basalt, and amygdaloidal basalt. The porphyritic basalt is medium to coarse-grained, with plagioclase and olivine phenocrysts, massive, blocky in appearance, and exposed in gentle slopes to steep cliffs. The vesicular basalt is a highly porous and friable rock type, which is dominant in the western, northern, and southeastern parts of the area. There is a paleosoil developed as a thin layer between the porphyritic basalt and vesicular basalt. The porphyritic-agglomerate basalt shows a high rate of spheroidal weathering and breaks easily to very small size material. The weathering and fracturing increase towards the major joints and layering. It is mostly found in the upper part, overlying the volcanic ash unit and underlying the ignimbrite/rhyolite unit. The porphyritic and scoriaceous agglomerate basalt crops out around Armanyia, and they are observed to be susceptible to local weathering and erosion. The units found around Yizaba Wein and Shotel Amba localities are dissected by faults oriented NNW–SSE, NNE–SSW, and E–W (Figs. 2 and 12).

The Tarmaber basalt, which is the most abundant in the study area, is mainly exposed in the western part of the area in the high-rising Tarmaber–Mezezo mountain chains. This rock formation forms vertical cliffs and ridges trending in the N–S direction and some E–W offsets (Fig. 2). It is highly weathered, jointed, and fractured and shows well-developed columnar joints. There are three sets of joints trending in the N–S, E–W and NE–SW directions, with vertical to sub-vertical dip angles. The upper ignimbrite unit crops out in the western part of the area overlying the Tarmaber basalt. The upper ignimbrite is fine-grained, light gray to light yellowish color, massive to bedded, highly weathered, and crossed by sub-vertical to vertical fractures.

The colluvial deposits are common along the upper pediments adjacent to cliffs, presumably transported downslope by the action of gravity and slope wash (Fig. 2). These deposits consist of unsorted to poorly sorted loose soil sediments and rock fragments, with large blocks of basalt toppled from upslope cliff faces. Some seepages or springs that drain from the highlands disappear in this thick colluvium material and re-emerge at the lower slope breaks or stream banks. Most of the seepages or springs also emerge along the contacts of the colluvium with the ignimbrite-volcanic ash unit.

The alluvial deposits are restricted along the major riverbeds, riverbanks, and their tributaries representing riverbeds and terraces (Fig. 2). The sediments found at the riverbed and riverbanks are dominated by coarser materials (such as sands, gravels, and boulders). This indicates that the streams are highly erosive and transport debris from the landslide zones. The deeply dissected gullies are filled by sediments up to several tens of meters thick, which consist mainly of colluvial and alluvial deposits.

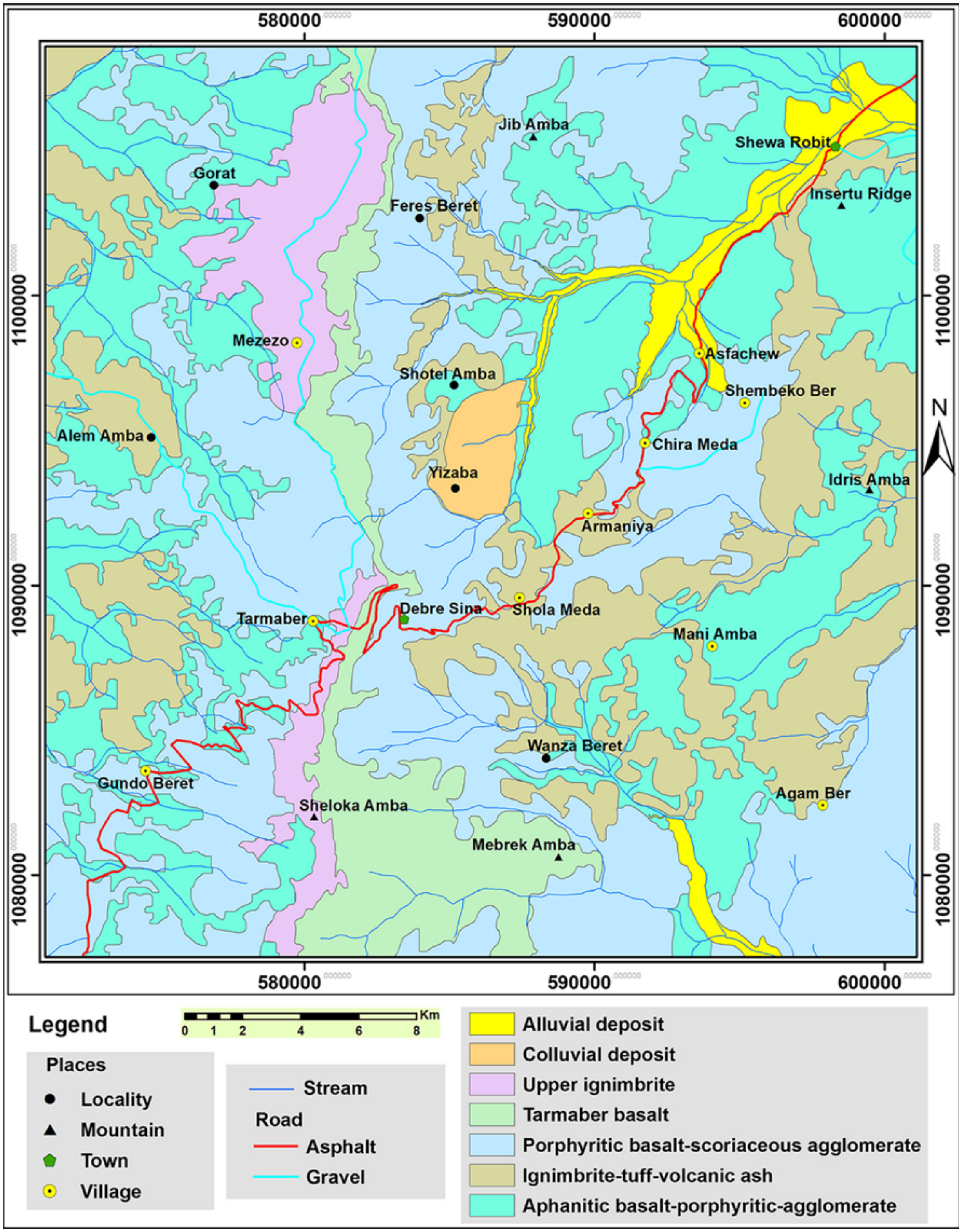

Fig. 2 Geological map of the study area

The geomorphology of the study area is very complex and strongly influenced by tectonics, rock weathering, and erosion. Due to the Quaternary tectonic uplift (Fubelli and Dramis 2015) and the related deepening of the rift, the hydrographic network increased the relief energy, giving rise to steep slopes and deeply cut valleys in the bedrock and thus predisposing the slopes to the development of mass movements. Some morphological aspects of the area have been visualized through the morphometric analysis of a 30-m resolution DEM using utilities of ArcGIS. The study area elevation ranges from 1153 m a.s.l. in the northeast and southeast lowlands to more than 3690 m a.s.l. in the western catchment boundary at the margin of the western rift escarpment (Fig. 3). The mean elevation is 2209 m a.s.l. with a standard

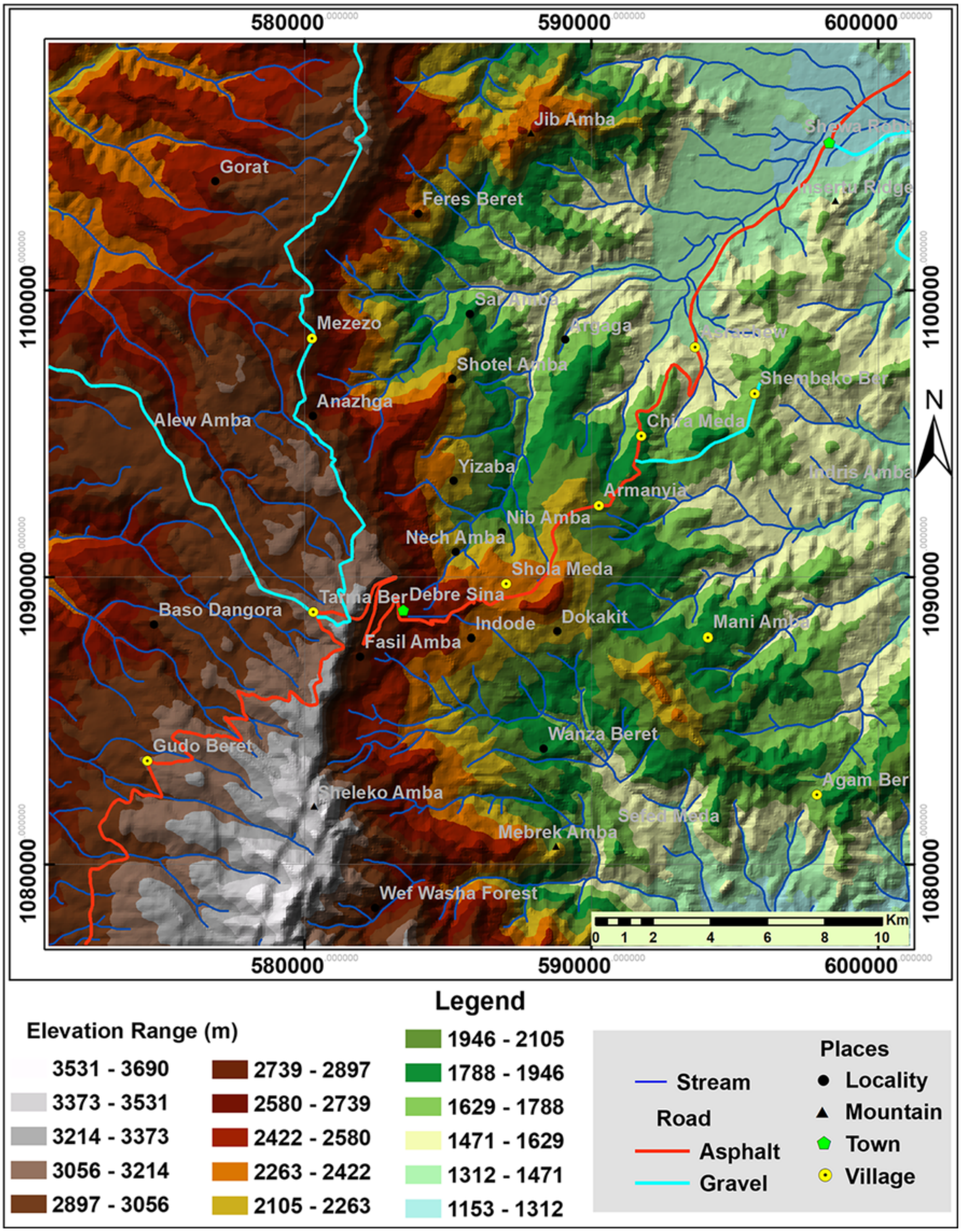

Fig. 3 Elevation map of the study area

deviation of 620 m. There is a high topographic relief of 2.54 km that is marked by deeply dissected gullies and channels, rugged topography, and high-altitude continuous ridge chains with steep escarpments. The land surface on the central part is characterized by rugged morphology and in the west is bordered by a high cliff. A gently to steeply sloping ground follows below the main steep escarpment and extends downslope towards the Dem Aytemashy river valley. The gullies located in the area form triangular-faceted landforms due to weathering and erosion processes.

These peculiar characteristics of the study area presumably denote complex landscape evolution in the geologic past. At very high elevation, there are mountain summits that usually consist of slightly to moderately weathered rocks whose shear strength is very high. The Debre Sina area is basically a warped plateau with slope gradient in the range of 0° to 63° with a mean value of 11.23° and standard deviation of 6.7° (Fig. 4). The slope range between 0° and 10° accounts for 26.54% of the area which represents the lowlands, flatlands, linear valleys, and plains in between relatively elevated hills. This constitutes mainly the lowlands in the northeast, west, and southwest; lower valleys and benches of major streams; and wide valley plains that stretch to the northeast and southeast. The slope class 10°–20° accounts for 49.58% of the area and marks small hills and gentle slopes at the lower parts of escarpment. The slope class ranging between 20° and 30° covers 20.47% of the area and denotes small scarps in deeply incised stream gorges. The slope class 30°–40° accounts for 2.43% of the area and belongs to prominent erosion and tectonic scarps, as well as elevated hills and ridges above gently

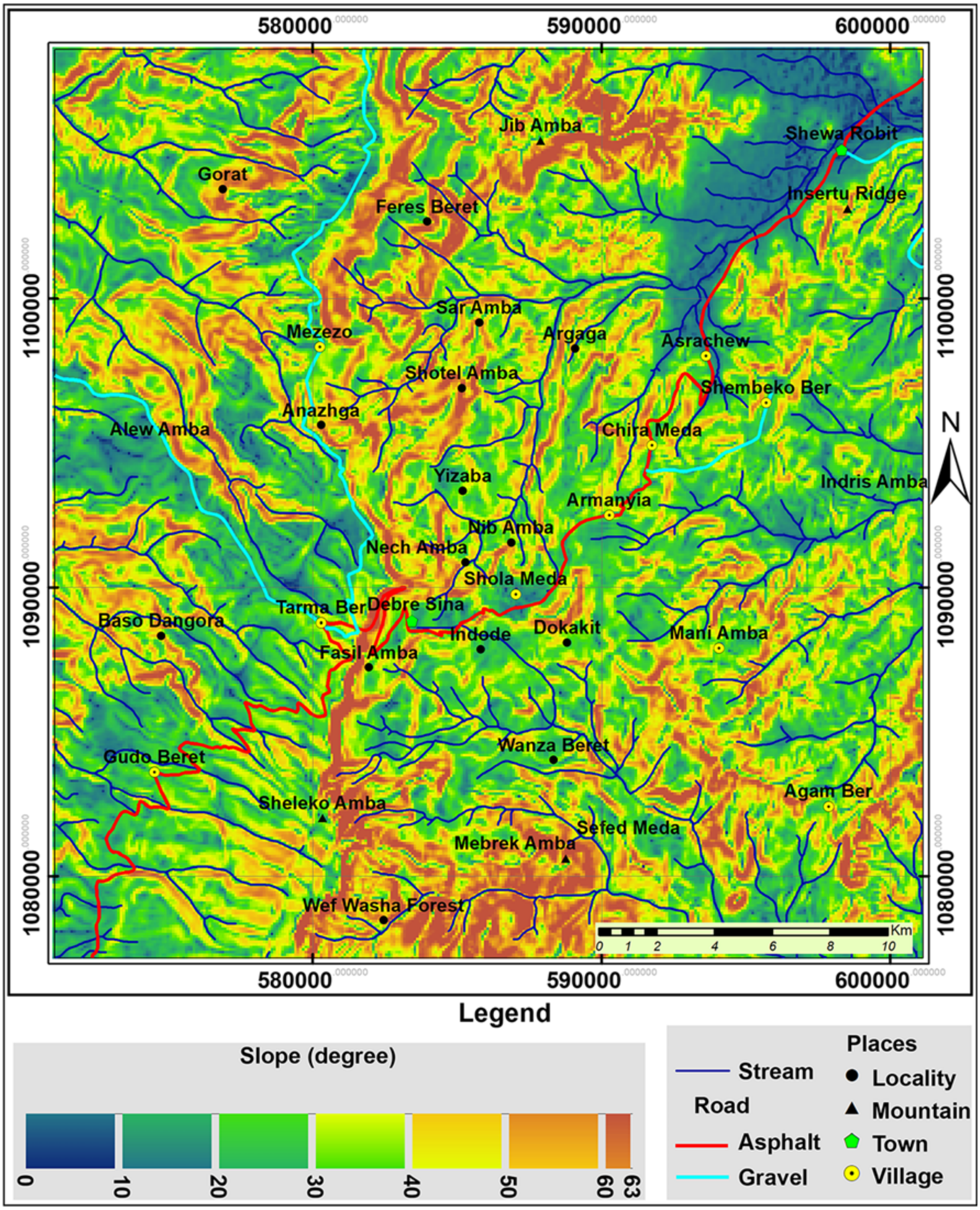

Fig. 4 Slope angle map of the study area

sloping grounds. The slope class 40°–50° accounts for 0.64% of the area and marks the upper slopes, local ridges, prominently mesas, and hills.

The highest slope gradient above 50°, which covers only 0.34% of the study area, is a characteristic of high-altitude continuous ridge chains with cliffs along the elevated mountains and volcanic centers and to some extent the deeply dissected channels. Slope aspect defines direct contact with sunlight and winds, affecting indirectly other factors that contribute to landslides, such as precipitation, soil moisture, vegetation covers, and soil thickness (Clerici et al. 2006). The mean slope aspect is 165° with a standard deviation of 105°. The computed slope aspect map was classified into nine directional quadrants (Fig. 5) as flat (− 1), north (0–35° to 324–360°), northeast (35–71°), east (71–107°), southeast (107–143°), south (143–216°), southwest (216–252°), west (252–288°), and northwest (288–324°). The east and southeast facing slope aspects are very widely distributed with frequency values of 22.5% and 19.2%, respectively. The slopes facing north, northeast, and south have the next higher frequency values, whereas slopes facing northwest, west, and southwest have low-frequency values.

Description, typology, and distribution of landslides

The distribution of landslides in the study area was found to be notably concentrated in the south and north vicinities of Debre Sina town (Fig. 6). Before the occurrence of the more recent landslides, there were observations of symptoms (such as tensile fissures in the soil) in the years 1977 and 1978. This was followed by a major development of landslide in late 1979 (EIGS 1979). Many landslides have remained active for a long period, and a considerable number of relict landslides were reactivated in 2004, 2005, 2006, 2007, 2014, and 2016 during intensive rainfall and tectonic activity (Woldearegay 2008; Abay and Barbieri 2012; Kropáček et al. 2015). The oral information of the local people indicates that the landslides in the study area have been active for at least the last 15 years. Following the Varnes (1978) classification, the most common types of landslides in the study area include (a) rotational slides, (b) translational slides, (c) rockfalls and toppling, and (d) debris and earth flow. The most spectacular ones were observed at Yizaba Wein, Shotel Amba, Nib Amba, Nech Amba, Wanza Beret, and Shola Meda areas (Fig. 6). Their main characteristics and the affected areas are briefly outlined below.

Yizaba Wein and Shotel Amba landslides

The largest landslide in the Debre Sina area, ca. 40 km^2 according to Woldearegay (2008), affected the localities of Yizaba Wein and Shotel Amba in September 2005. Here, the slope shows clear morphological evidence of a deep-seated landslide (e.g., breaks on the slope, depressions, terraced surfaces, and convex-concave forms) (Fig. 7b, c). The landslide, which involves a large portion of the slope from the top to the valley bottom, consists of two distinct and compound blocks: (i) an older block and (ii) a more active one that underlies the former one (Fig. 7a). The active block can be classified as a roto-translational rock slide (Borgatti et al. 2006) and is characterized by a semi-circular head scarp (crown at 2457 m a.s.l.). Its mid to lower part is concealed by a secondary active debris slide and debris/earth flow (Fig. 7c). During the fieldwork, relatively fresh cracks 20–50 cm wide were also identified in the lower part of the slope close to the debris flow (Fig. 7c).

The Yizaba Wein and Shotel Amba landslide is truncated by the most recent and active body that involves a significant part of the slope and is characterized by fresh morphological features (Fig. 7a, b). Furthermore, the rock mass moved along the frontal part of the landslide causes the detachment of rock fragments and blocks (rockfall, rock slide, and block toppling), which bounce towards the river (Fig. 7b). Additionally, the constant deepening of the streams causes local undercutting of the cliff/sliding block and triggers new shallow landslides from the left bank of the watercourse, with a general retrogressive trend (Fig. 7d).

The landslide was initiated in the heavily fractured porphyritic basalt and highly shattered ignimbrite and volcanic ash units. The bedrock is mostly covered by colluvium deriving from the uppermost steep slope and cliff edges. The landslides were mostly associated with colluvial materials, including boulders and a higher proportion of granular soil. The hydrogeological conditions of the terrains are favorable for the development of seepage within the pyroclastic sediments (tuff and pumice horizons) and unconsolidated deposits during periods of rainfalls.

Nib Amba landslide

The Nib Amba area is widely affected by active and dormant landslides of different types and sizes including translational and rotational slides, debris/earth slides and flows, and rockfalls. Superimposed landslide bodies confirm that the spatial distribution of the recent landslides is frequently influenced by the presence of older landslides. The 2005–2007 events were characterized by multiple retrogressive translational slides in the upper part and multiple advancing rotational slides in the lower part, especially along the stream banks (Fig. 8b, c). In May 2016, rainstorms triggered an earth flow with a volume of several cubic kilometers and other landslides such as debris flow, shallow slides, and rockfalls which caused damage to dwellings, agricultural lands, and the natural environment (Fig. 8a, d).

Most failures have developed due to the soft interlayered pyroclastic sediments (tuff and pumice) overcharged by the

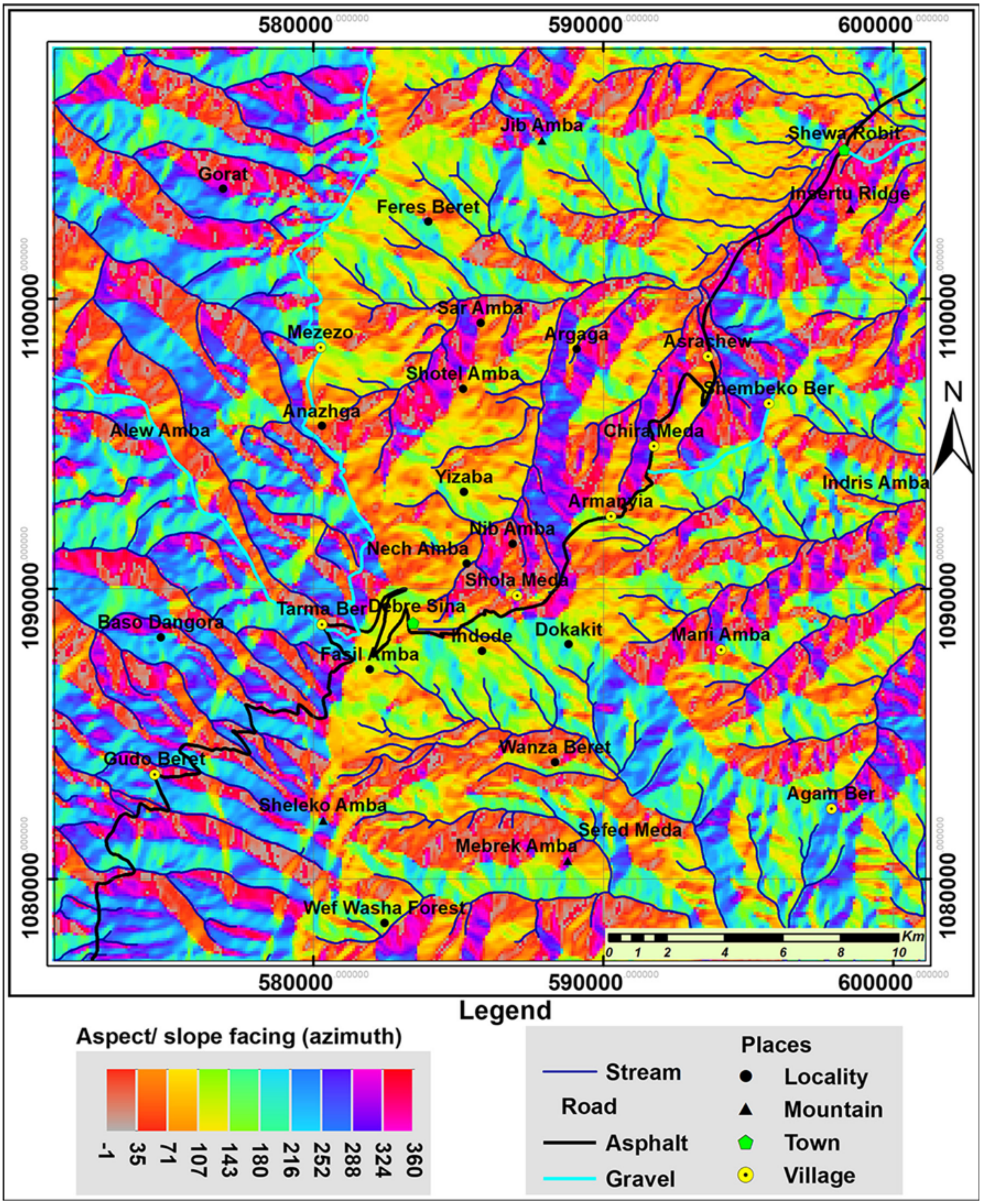

Fig. 5 Slope aspect map of the study area

abundant rainfall. In 2005–2007, reactivated landslides destroyed farmland and dwellings in the gorge of the Koda Menkeriya river (Fig. 8b). Outcropping lithology and bedrock structure together with the rugged topography were responsible for slope instability in this locality. The landslides were mostly associated with soft interlayered pyroclastic sediments (tuff and pumice) and black cotton soil. A quasi-rotational slide created a stagnant pond at the frontal part of a slope movement (Fig. 8c).

Nech Amba landslide

Shallow to deep landslides in the Nech Amba area involve weaker material (Fig. 6), mostly composed of transported loose deposits with a higher proportion of clay underlain by pyroclastic sediment and agglomerate basalt (Fig. 9a, b). In some areas, the failures are concentrated along streams and riverbanks within deep gullies. Debris flows, rock slides, and retrogressive rotational slides are

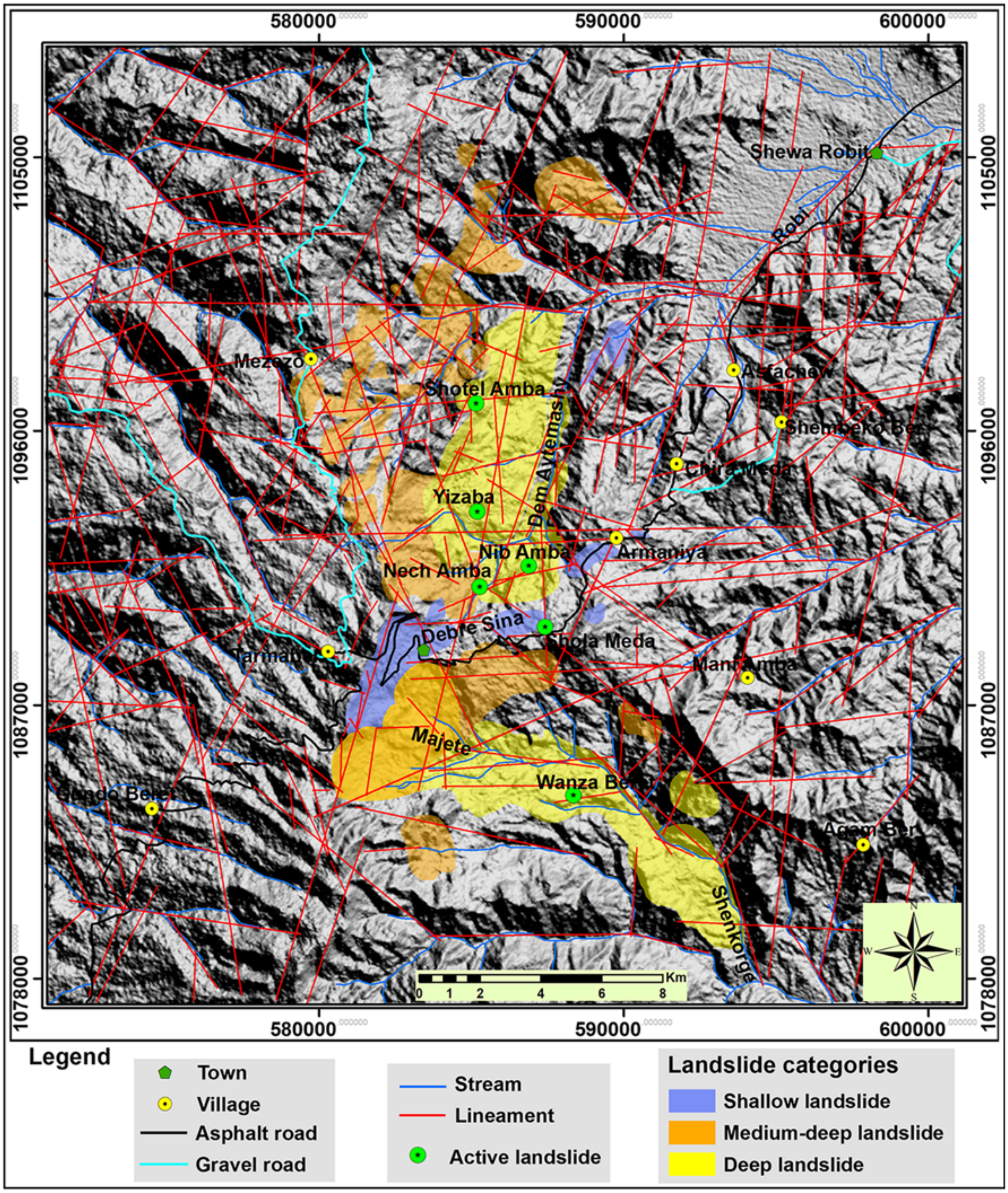

Fig. 6 Landslide inventory and morphostructural map of the study area

common in the area. These landslides are likely influenced by the presence of weathered rocks and susceptible volcanic ash. The landslide was reactivated after heavy rainfall on May 6, 2016, and a new episode of high-potential landslides occurred along the crowns and riverbanks. Farmland and dwellings were devastated by reactivated landslides in 2016. Moreover, there are irregular tension cracks in buildings and tilted houses found near the riverbank.

Wanza Beret landslide

The most remarkable and probably the second largest slope failure, a huge earth slide, was recorded in Wanza Beret, highly rugged, deeply incised by various gullies and rivers, and subjected to severe erosion. The main landslide body is currently about 200 m wide and 70 m long (Fig. 9d). Various other types of landslides (quasi-rotational slides, debris slides, earth slides, debris flows, and earth flows) were identified in

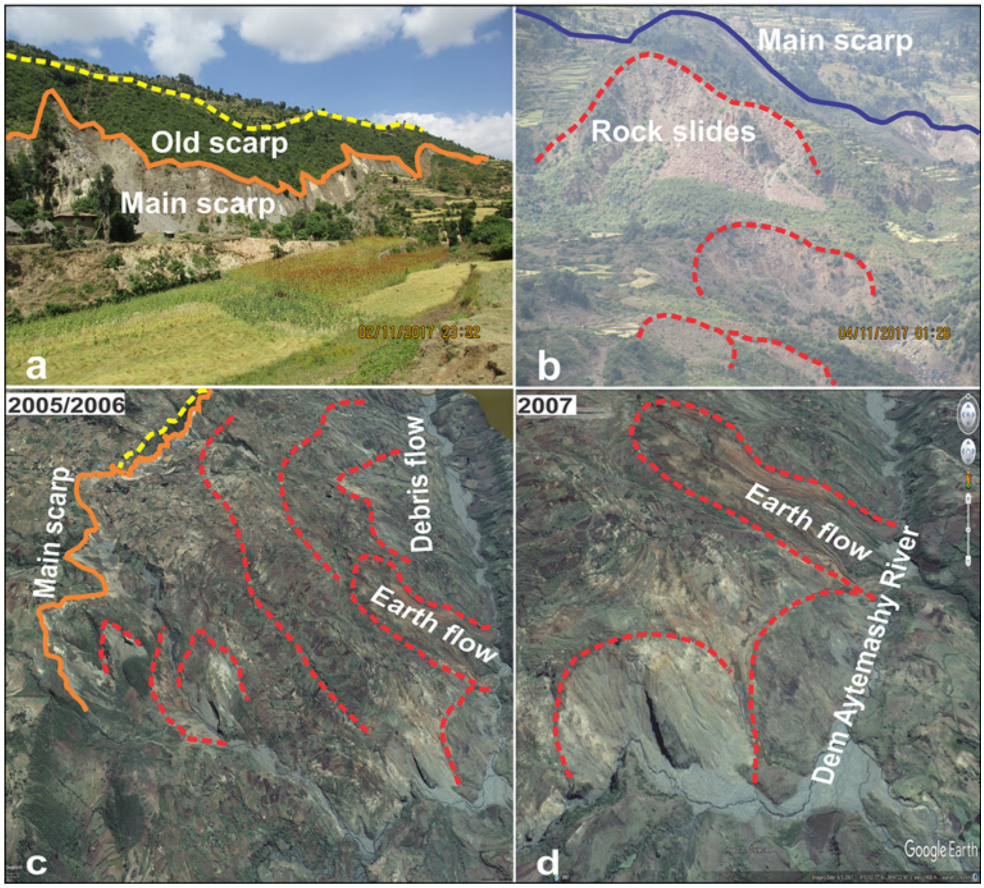

Fig. 7 **a** Translational slide occurred in 2005. **b** Roto-translational rock slide and rockfalls. **c** Yizaba Wein and Shotel Amba convex-concave landslides. **d** Rotational slide and earth flow dipping downslope towards Dem Aytemashy river

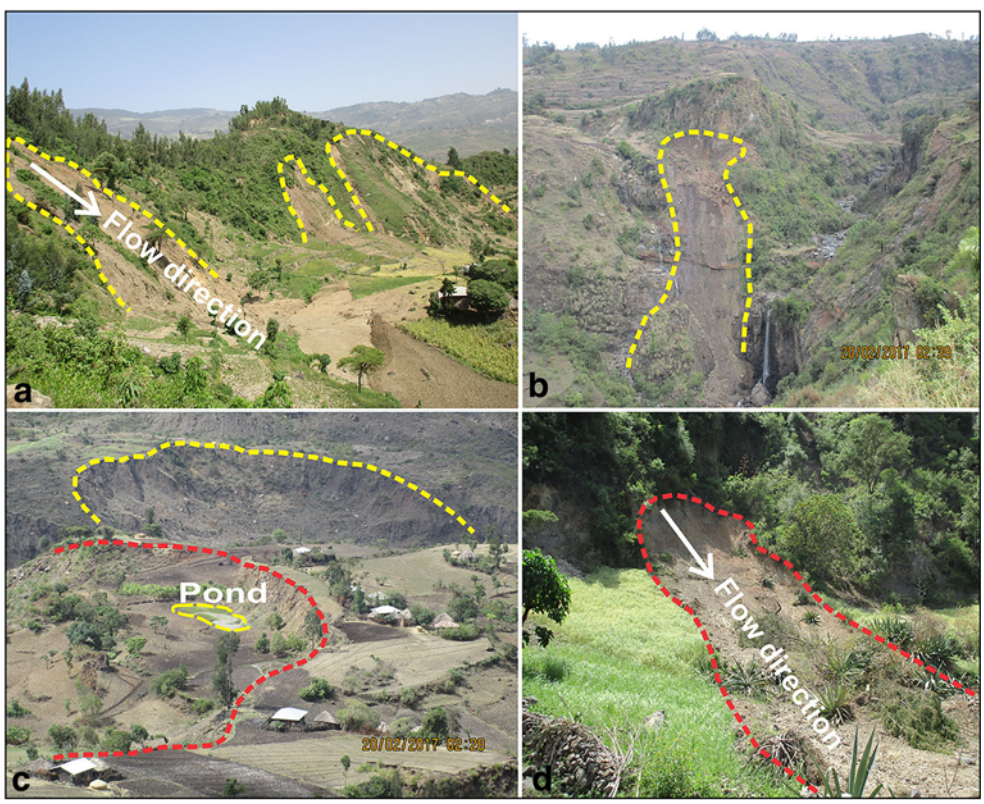

Fig. 8 **a** Debris flow demolished agricultural land in Nib Amba. **b** Rockslide in Nib Amba. **c** Deep-seated rotational slides form a pond at the lower part of the slide zone. **d** Earth flow demolished farmland

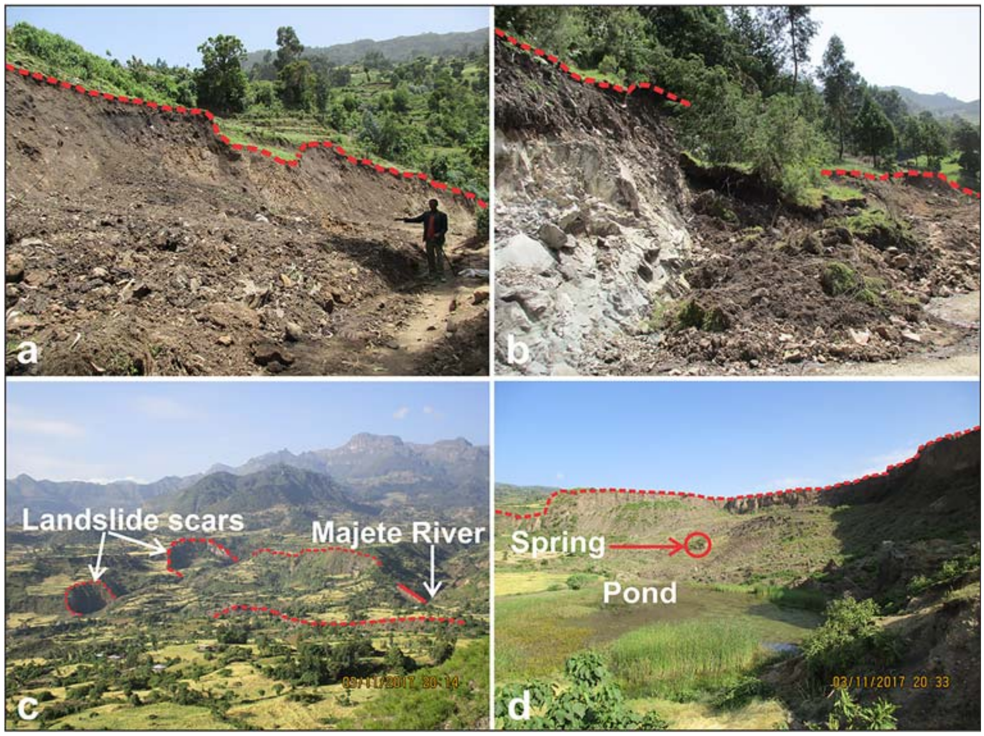

Fig. 9 **a**, **b** Earth slides around Nech Amba area occurred on May 6, 2016. **c** Pre-existing landslide scars and active landslides in the gorge of the Majete river. **d** A quasi-rotational slide widening retrogressively

this area. A quasi-rotational slide is one which the displacement of the compound block would have opened up a depression that was rapidly infilled with debris which continues for some time after (Palmer et al. 2007). This occurs in limited cases where the thickness of unconsolidated deposits is thick enough to generate deep failure surfaces (Woldearegay et al. 2006). Slope failures in highly weathered basalt, pyroclastic sediments, and unconsolidated material are induced by the undercutting of the Majete river and its tributaries (Fig. 9c). The thickness of unconsolidated deposits has a significant role to generate deep sliding surfaces. Farmland and dwellings were destroyed by the reactivated dormant landslides in 2005–2007 (Fig. 9c). These landslides were mostly associated with colluvial inclusions of boulders and a higher proportion of granular soil. A quasi-rotational slide has created a stagnant pond at the lower part of the slope (Fig. 9d).

Shola Meda landslide

The Shola Meda landslide is considered the evolution of ground cracking and a slow creeping zone (Fig. 10c). There are scars occurring intermittently with smaller magnitude. In Shola Meda, an asphalt road crossing Tarmaber–Debre Sina–Armaniya–Shewa Robit cracked at several places and has also been damaged (Fig. 10d). Furthermore, a gravel road under construction heading from Debre Sina to Shotel Amba was sliding at several places on May 6, 2016, following the heavy rainfall (Fig. 10a, b). A considerable number of relict landslides in the Debre Sina area such as Sina, Yizaba Wein, and Shotel Amba localities were reactivated during the construction of a gravel road along the Debre Sina–Shotel Amba line. In addition to the active tectonics and seismic forces, the slope modification during the construction of the gravel road caused a man-induced slope failure. There are several closely spaced, shallow landslides and ground cracks in black cotton soil, a dark gray in color, fine to very fine-grained clay, slightly moist to moist and rough in texture. During the fieldwork, the slope showed widespread instability conditions with ground tension cracks, rock slides, and earth slides (Fig. 10a–c).

Discussion

The failure mechanisms of the large-scale landslides of the Debre Sina area were evaluated based on the context of geology (lithology and structure), kinematic analysis of discontinuities, rainfall, and earthquakes.

Lithology and structure

Several landslide occurrences are observed in the ignimbrite-tuff-volcanic ash and colluvial deposit litho-stratigraphic units. The pyroclastics contain lapilli tuff, tuff breccia, and tuffaceous rocks, which are susceptible to slaking, giving rise to landslides. The highly weathered basaltic rocks and unconsolidated materials in steep slope areas are mostly associated with the high landslide and rockfall susceptibility zone. The

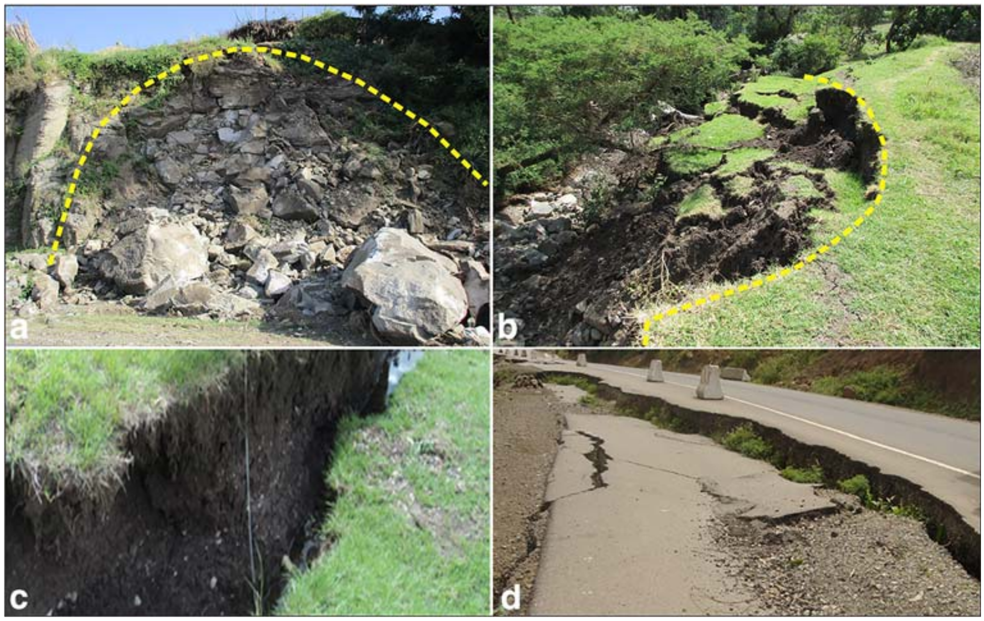

Fig. 10 **a** Photographs showing rock slides around Armaniya along the asphalt roadside. **b** Earth slides. **c** Tension cracks in a black cotton soil at Shola Meda. **d** Asphalt road collapsed along Debre Sina and Armaniya

porphyritic basalt-scoriaceous agglomerate cliffs that rise above the ignimbrite-tuff-volcanic ash and colluvial deposit are particularly subject to considerable rockfalls and topplings as well as rock slides (Fig. 7b). The area covered with the Tarmaber basalt is least affected by landslide apart from some rockfalls at the base of the cliffs. Field observations confirmed that many types of landslides are densely distributed in the colluvial deposits, ignimbrite-tuff-volcanic ash, porphyritic basalt, and scoriaceous agglomerate units. This can be attributed to the high degree of weathering and fracturing, which in turn reduces the strength of rocks. The intense fracturing and presence of faults favor an easy movement along existing fault planes during saturation of the rocks or soils and during seismic events or a combination of both conditions. The geological structures are coinciding with the head scarp of the old and new failure planes, and several slide incidences also are observed in the ignimbrite-tuff-volcanic ash and porphyritic basalt-scoriaceous agglomerate units. The structural setting of the study area is associated with the extensional fault system of the rift margin that bound the northwestern Ethiopian plateau to the west. The major and longest normal faults are mainly composed of many overstepping small fault segments propagating laterally, increasing in size and amount of displacement. The main geological structures identified are faults, lineaments, and fractures/joints (Fig. 12). A plot of contoured pole concentrations and a rose diagram of 360 discontinuity measurements from the landslide areas are shown in Fig. 11d.

There are four dominant sets of discontinuities (N–S, E–W, NE–SW, and NW–SE) (Fig. 11a), which are mainly vertical to sub-vertical (tectonic joints). The E–W and N–S striking lineaments record the highest frequency and cut across by the NW–SE trending lineaments (Fig. 12). The N–S joint set dominantly dips towards E, the E–W set dips either N or S, the NE–SW set dominantly dips towards SE, and the NW–SE set dominantly dips towards NE. The dip angle ranges from 10° to 90° (Fig. 11b). The N–S trending normal faults are arranged in a stepwise system towards east, which controls the morphology of the slope of the rift margin escarpment. The major normal faults dip approximately 85°, 80°, and 60° towards the east; they cross the Yizaba Wein and Shotel Amba large-scale landslides. The slope instability in the area is related to these faults, joints, and fracture zones. Plots of poles cluster around the periphery of the stereographic net and exhibit three maxima (Fig. 11c, d) that may suggest the occurrence of four trends of faulting: N–S, E–W, NE–SW, and NW–SE. Plotting around the periphery of the stereographic net indicates steep dips (Fig. 11d). Furthermore, the contoured diagram exhibits three maxima that resolve into three great circle girdles. This possibly signifies vertical to sub-vertical fractures at the intersection of joints resulting in steep hydraulic gradient of groundwater. This situation might lead to a rock topplings from the surrounding steep cliffs down to the river valley.

In general, a frequency plot of all joint strike data shows widely ranging trends that indicate fracturing of the lithologies in every direction (Fig. 11a). The landslides displacement is orthogonal to the NNE–SSW, and N–S striking normal fault systems that are affected by NW and NE striking transtensional components (Kiros et al. 2018). The interaction of these fault systems produced a complex displacement across and along the escarpment, manifesting oblique continental rifting. The rock slopes stability is greatly affected by the discontinuities and their interrelationship with the slope (Hoek and Bray 1981). The discontinuities in the area are generally open, smoothly undulating, lowly to highly

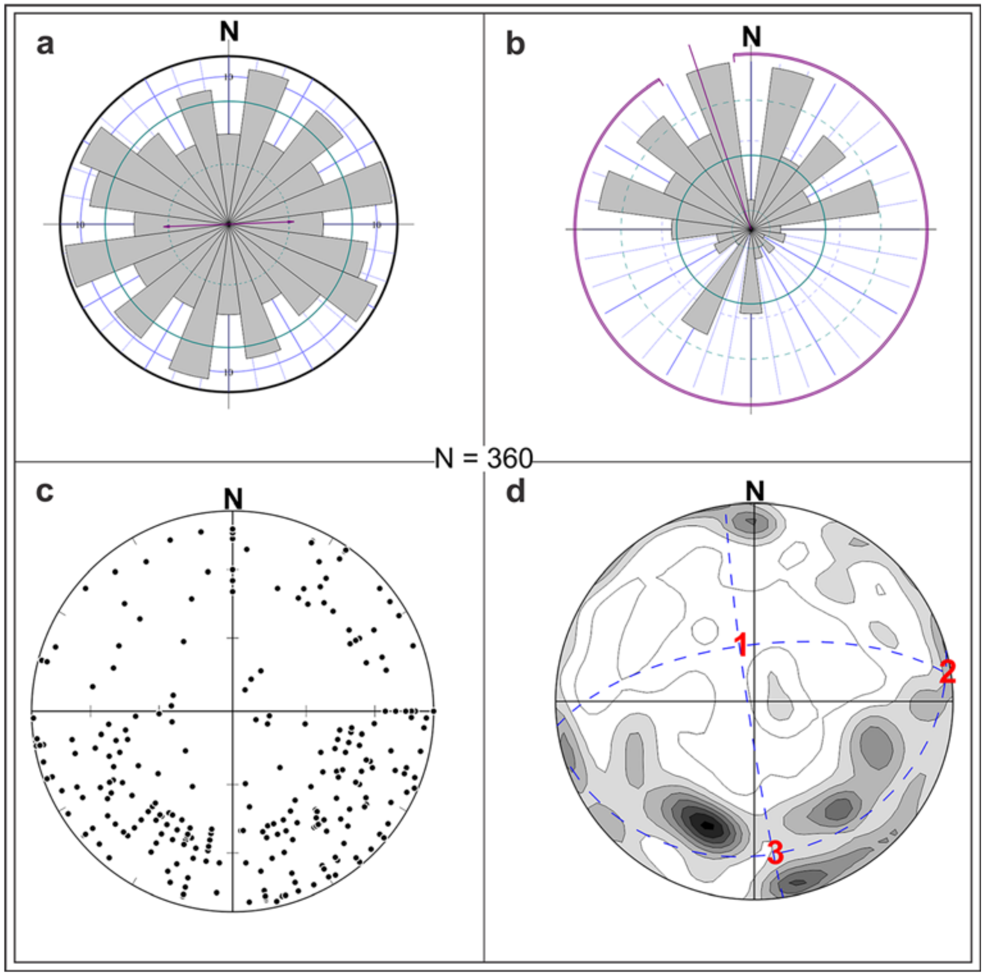

Fig. 11 Stereographic projection of joints/fractures orientation data. **a** Rose diagram showing strike direction. **b** Rose diagram showing dip direction. **c** Plots of poles. **d** Pole density contour diagram

persistent, and intersecting each other. This is a crucial factor in slope stability, acting as either conduit for groundwater flow or as aquitards. The NNE to NE fracture systems are very well-marked by topography breaks in the area. Landslides are strongly oriented NNE–SSW and N–S, thus corresponding with the most consistent lineament set.

Elevation, slope angle, and aspect

The distribution of landslides in relation to elevation is frequent in the middle elevation (1800–2500 m). At intermediate elevations, slopes tend to be covered by ignimbrite-tuff-volcanic ash, porphyritic basalt, and colluvium, which are more prone to landsliding. The landslide risk is little to average at very low elevations because the terrain itself is flat, although it is covered by layers of colluvial-alluvial soils, but higher density springs and intense undercutting of the bottom of the slope at the intermediate elevations initiate slope failure. The highest density of landslides falls in the elevation class 1800–2500 m a.s.l., followed by elevation class 2500–3000 m a.s.l. But, the elevation class 1153–1500 m a.s.l. is characterized by fewer landslide events (Figs. 3 and 14). The high density of landslides is mainly related to the presence of highly fractured porphyritic basalt and highly shattered ignimbrite as well as volcanic ashes which are susceptible to slaking. Furthermore, the springs that emerge in the elevated parts of the area also suggest that the hydrostatic pressure of groundwater can be a triggering factor to the landslides. Most of the landslides occur in the slope gradients that range between 10° and 40°, and the highest frequency of landslides is evident in the areas with slope gradient ranging between 30° and 40° (Fig. 4). The density of landslides in the study area with respect to aspect reaches the maximum values on the east-facing slopes, followed by those facing southeast (Fig. 5). The easterly and southeasterly facing slopes receive a high amount of sunlight and rainfall. This favors landsliding due to fault orientation dipping towards the east, increased rate of saturation, and weathering, particularly in loose pyroclastic sediments and colluvial deposits.

Rainfall

To determine the effect of rainfall on landslide occurrence in the area, the monthly rainfall of the Debre Sina meteorological

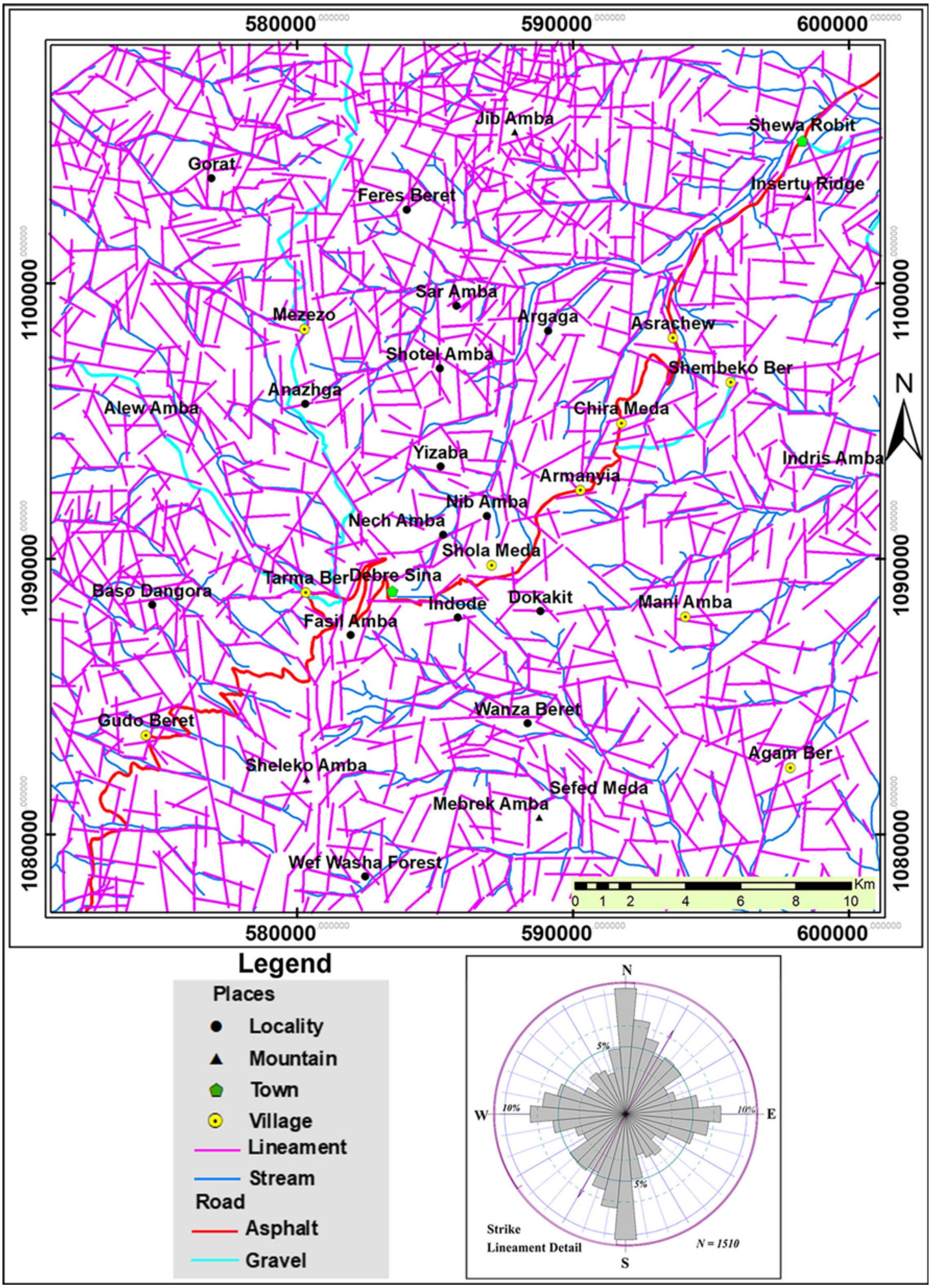

Fig. 12 Lineament map of the study area

station was analyzed. The dates of previously occurred landslides in the area were compiled from previous studies (EIGS 1979; Gebreselassie 2007; Woldearegay 2008; Abay and Barbieri 2012) and interviews with local residents during fieldwork. The hydrological year 1997 was exceptional in terms of the amount of rain (3593 mm). The most evident reactivations of older landslides are the movements that occurred in spring and summer 2005–2016 following long-lasting and above-average precipitation (Fig. 13). Localized landslide occurrences are common in every rainfall period in the rift margin, including the Debre Sina area, especially along stream banks and road cuts. The heavy rainfalls of May 6 and July 27, 2016 have triggered several shallow to medium-depth landslides in different parts of the area, mainly referable to earth/debris flows, rockfalls, and earth/debris slides. Also, there was a flash flood in Shewa Robit village in 2016, where the river burst its banks and caused damages to built-up structures along the stream. Most of the landslide incidences in the area occurred in the peak wet season (Fig. 13). All landslides occurred when the annual rainfall was greater than the long-term average rainfall except for the hydrological year 2016. This indicates that precipitation is one of the potential triggering factors for the slope failure in the Debre Sina area. Besides, the concave shape of the terrain is enhancing the convergence of groundwater flow into the landslide area.

The landslides of May 6 and July 27, 2016 occurred after 24 h of continuous rainfall of 54 mm and 60 mm, respectively. This shows that rainfall intensity alone could be an issue for shallow landslides, but not for very large deep-seated failures. The relationship between rainfall and landslide events indicates that deep-seated failures prevail after a longer period of intensive rainfall. A single precipitation event is unlikely to trigger a deep-seated slope failure of large extent. Most of the landslides shown in Fig. 13 do not have known month or date of occurrences except the landslides in 2016. The inlet graph of the mean monthly precipitation in Fig. 13 shows periods of intensive rainfall in July, August, and November (1997). The mean annual precipitation for the whole period is 1812 mm and marked by a horizontal black broken line, as shown in Fig. 13.

Earthquakes

The central highlands of Ethiopia are in close proximity to the most seismically active regions of the country, such as the Afar Triangle and the MER, where well-documented damaging earthquakes are common (Samuel et al. 2012). The northwestern plateau and southeastern plateau are split by the active East African Rift Valley, which has a history of generating large earthquakes (Zygmunt et al. 2014). More than 90% of the seismic and volcanic activities are connected with the rifts, but the seismic hazards to life and property and the greatest damaging effects are found on the plateaus where the majority of the population resides. The Debre Sina area is known for its seismic activities recorded in chronicles as well as in measured records. The earthquake events that occurred between April 1841 and December 1842 (Gouin 1979) along the plateau's escarpment triggered landslides and rockfalls that destroyed the town of Ankober, which is located nearby the study area (Fig. 14). The causes of such slope failures were

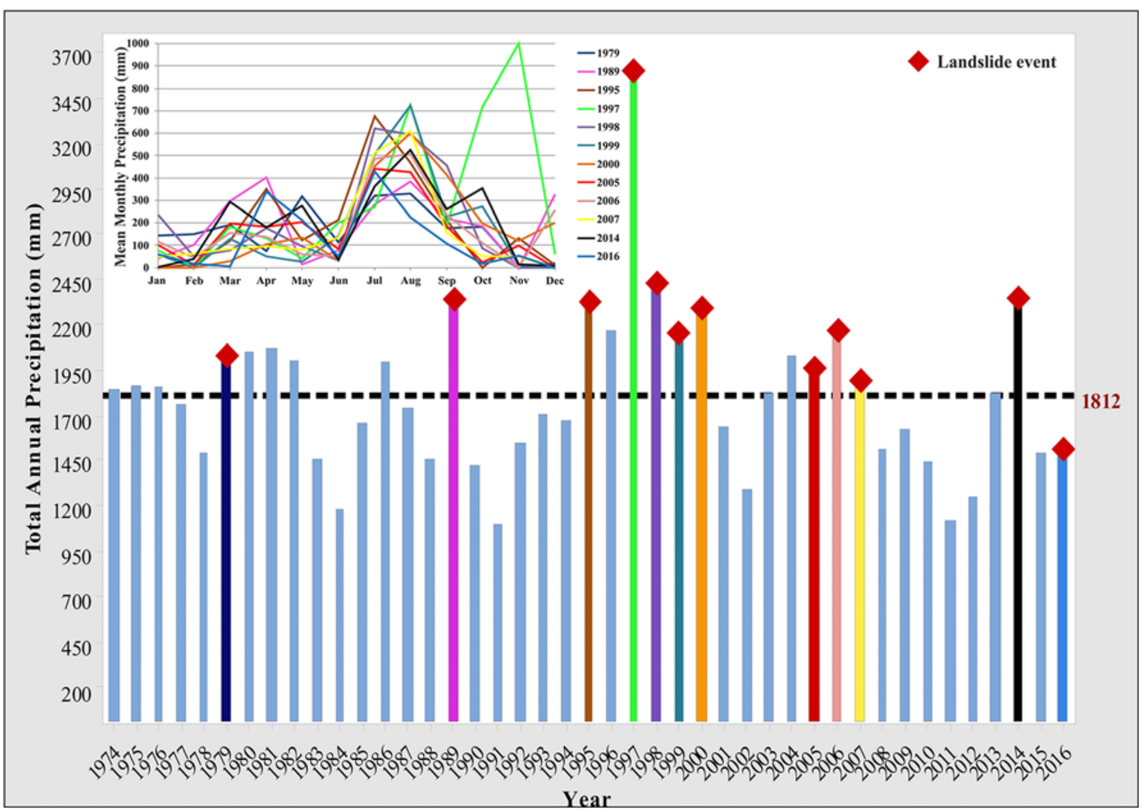

Fig. 13 Rainfall data from the Debre Sina station from 1974 to 2016 compared with landslide events

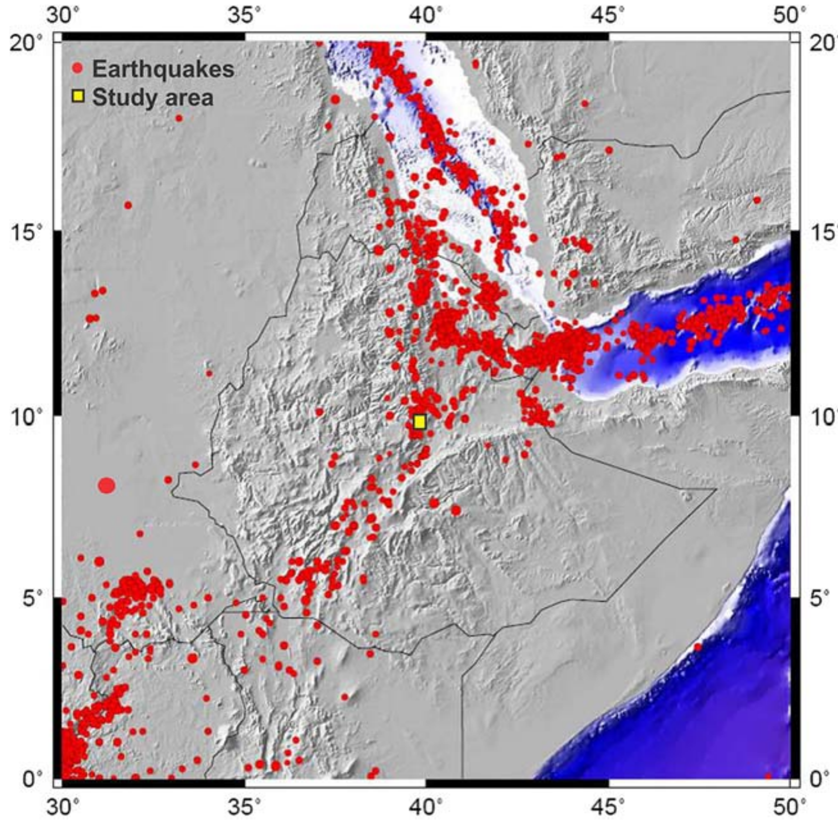

Fig. 14 Recorded earthquakes in the East African region from 1842 to 2011 (source: EAGLE data)

aggravated by heavy rains that had saturated the thin layer of clayish soil, precariously exposed along very steep slopes (Gouin 1979). During February 1974, tremors were reported in the Debre Birhan - Debre Sina region; some of these tremors were also felt in Addis Ababa (Alemayehu et al. 2012). Such tremors were caused by a sequence of earthquakes with magnitudes less than 4.5 originating from the region to the north and northwest of Debre Sina. This portrays that the effects of continuous shaking, even if light, on slopes of marginal stability, are cumulative.

According to Ayele et al. (2009), an earthquake of magnitude 5.0 Ml ruptured in an area 25 km northwest of the Ankober town at 17:56:07 GMT on 19 September 2009. The tremor was recorded in Addis Ababa, about 160 km from the epicenter. Furthermore, the area has been reported to have experienced a 6.0 magnitude earthquake in 1983. This is the maximum recorded from the area where the tectonic stress is mostly released by smaller magnitude shocks (Ayele 2009). During the fieldwork, interviewed local people and district administrators regarding the reactivated landslide in 2016 said that there were earthquakes shaking on 29 October 2015, 24 January 2016, and 1 May 2016, in the Debre Sina area and surroundings. This is in good agreement with suggestions by Kropáček et al. (2015) that the sliding events are driven by a combination of geologic and tectonic predispositions together with external factors such as long-term water saturation and seismic events. Figure 14 shows that a concentration of epicenters follows the main Ethiopian Rift structures. However, the epicenter distribution is more concentrated along the northeastern and western escarpment margin. Faults of the rift margin suffer from occasional earthquake tremors leading to the activation of unstable ground. Furthermore, there are several earthquake tremors recorded in the period 2005, 2006, 2016, and 2017 in the region. Out of these, the seismic tremor known to have been felt in the area close to the time of the deep-seated landslide that took place on 13 September 2005 in the Debre Sina area (Woldearegay 2008) is that of the major seismo-tectonic event in north-central Afar, in September 2005 (Yirgu et al. 2006). Although the earthquake around the time of the main deep-seated landslide occurred afterward, foreshocks of lower magnitude could have brought about a certain degree of instability in the already susceptible terrain. As reported by Ayele et al. (2009) and supported by subsequent researchers such as Yirgu et al. (2006), and Abay and Barbieri (2012), the tectonic activity and earthquakes might also be related to the activation of landslides in the form of deep-seated gravitational creep. Particularly in the Debre Sina area, the role of tectonic activity 2016 inducing landslides has been significant. The historical earthquakes distribution can indicate that the seismic hazard in the central-western highlands of Ethiopia is even higher. As there are intensive urban and infrastructural developments taking place along hills and rugged mountains in the study area and surroundings, very serious attention is required to consider the seismic hazard in the area during planning, design, and construction phases.

Conclusions

The study area is located along the Rift margin escarpment, a zone of notably high potential for landslides. It is flanked by the lower and upper normal faults and the Tarmaber–Mezezo mountain chain. This article presents six typical examples of recent slope movements in the area. The studied landslide areas have been evaluated in terms of their historical development, current status (based on the field survey results), and geological and topographical conditions. Deeper landslides are found in Yizaba Wein, Shotel Amba, Nib Amba, Nech Amba, and Wanza Beret areas, whereas shallower depth landslides are found in the Shola Meda area.

The area is covered by volcanic rocks and superficial deposits ranging in age from Tertiary to the recent. The landsliding events were driven by a combination of geologic and tectonic predispositions, together with external factors such as long-term water saturation and/or seismic events. The rocks exhibit a variety of planar discontinuities that originated during the volcanic formation and subsequent tectonic disturbances. The presence of highly fractured porphyritic-agglomeratic basalt, highly shattered ignimbrite, and volcanic ash, which are prone to water absorption and susceptible to slaking, was identified as one of the reasons for a high concentration of landslides and main triggering factors of reactivation in the observed cases. Therefore, it is evident that the inherent variation in the physical property of the lithologic sequence and their structures influence the slope stability.

Overall assessment of the morphometric analysis revealed that the slopes ranging from 10° to 40°, with an elevation of 1800–2500 m and aspect to east and southeast, are highly prone to sliding. The study area is densely traversed by faults and lineaments with a variable pattern that denotes the formation of the variable hydraulic system affecting mechanisms of surface and groundwater paths and thus degrades rock mass strength but also increases the weight of the slope mass, i.e., increasing pull of gravity. The landslide displacement is orthogonal to NNE–SSW, and N–S striking normal fault systems affected by NW and NE striking trans-tensional components.

In general, the deep-seated translational and rotational landslides of the area are controlled by different predisposing factors such as (i) geological-structural setting, (ii) complex morphology of the slope, (iii) presence of closely spaced normal fault segments with steep slope angles, and (iv) deepening of the Dem Aytemashy, Majete and Shenkorge streams (active erosion and gullying). This study shows the importance of recognizing both the predisposing factors and failure mechanisms along rift margins and highland terrains linked to deep-seated potential landslides and their disastrous consequences.

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